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(54) **NVRAM DATA ORGANIZATION USING SELF-DESCRIBING ENTITIES FOR PREDICTABLE RECOVERY AFTER POWER-LOSS**

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G06F 3/06 (2006.01)
G06F 12/02 (2006.01)

(52) **U.S. Cl.**
CPC ***G06F 3/0619*** (2013.01); ***G06F 3/065*** (2013.01); ***G06F 3/0688*** (2013.01); ***G06F 12/0246*** (2013.01); *G06F 2211/1038* (2013.01)

(58) **Field of Classification Search**
CPC G06F 12/0246; G06F 2211/1038; G06F 11/1471
USPC 711/104, 114, 162
See application file for complete search history.

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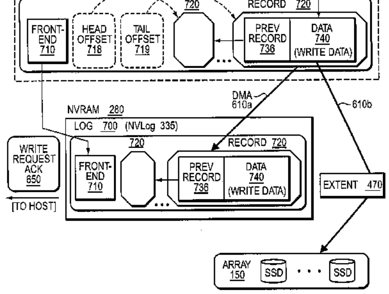
(57) **ABSTRACT**

In one embodiment, a node coupled to a plurality of solid state drives (SSDs) executes a storage input/output (I/O) stack having a plurality of layers. Write data associated with one or more write requests to the SSDs is stored in a volatile log. The write data is organized into one or more extents that are copied to the SSDs. The volatile log has a front-end and a set of records with metadata. The metadata includes a head offset referencing an initial record and a tail offset referencing a final record. A portion of the one or more write requests including the write data is copied to a non-volatile log maintained in a non-volatile random access memory (NVRAM). The front-end and the set of records from the volatile log are copied, but the head offset and the tail offset are not, to reduce an amount of metadata copied to the NVRAM.

20 Claims, 9 Drawing Sheets



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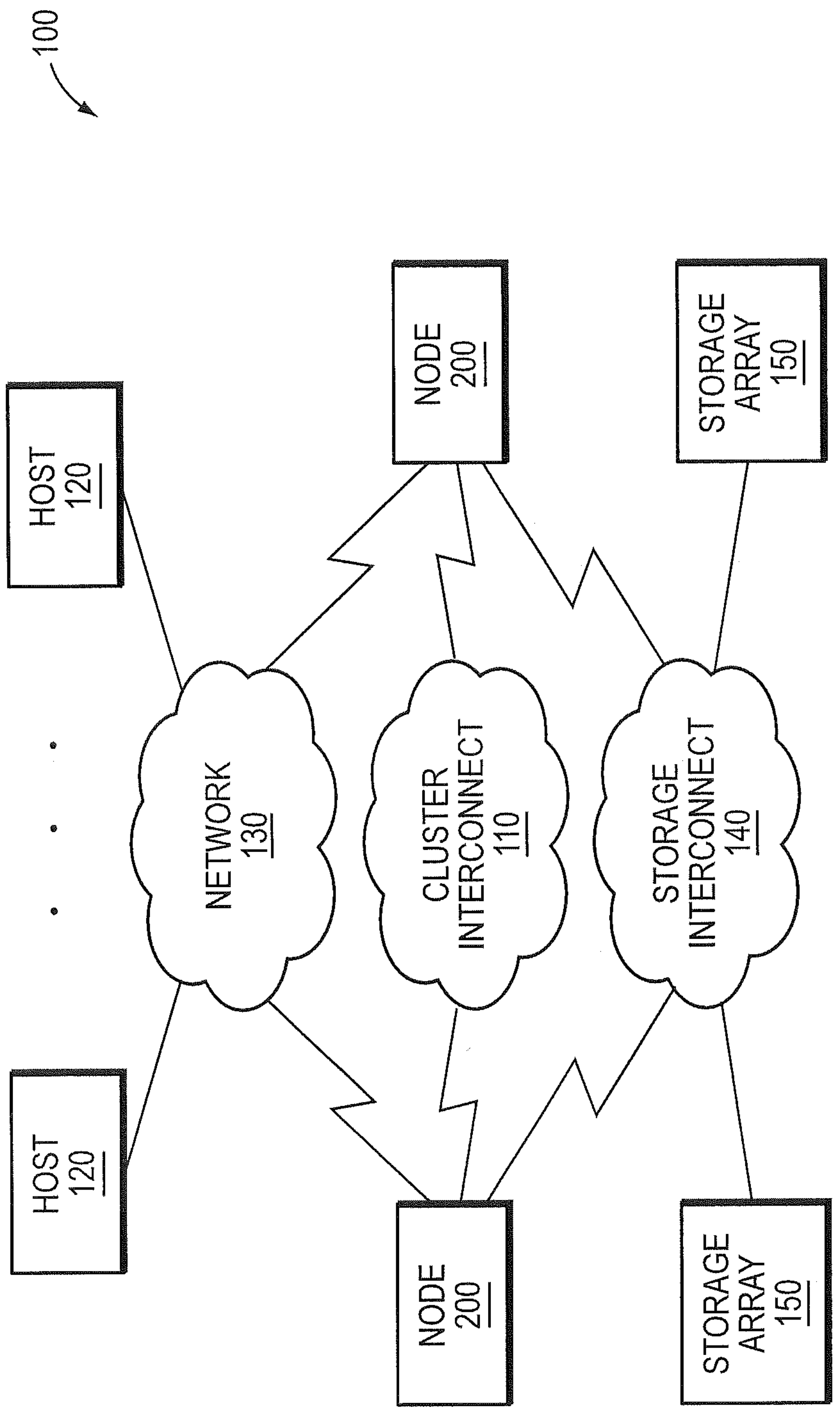

100
HOST 120
HOST 120
NETWORK 130
NODE 200
NODE 200
CLUSTER INTERCONNECT 110
STORAGE INTERCONNECT 140
STORAGE ARRAY 150
STORAGE ARRAY 150

FIG. 1

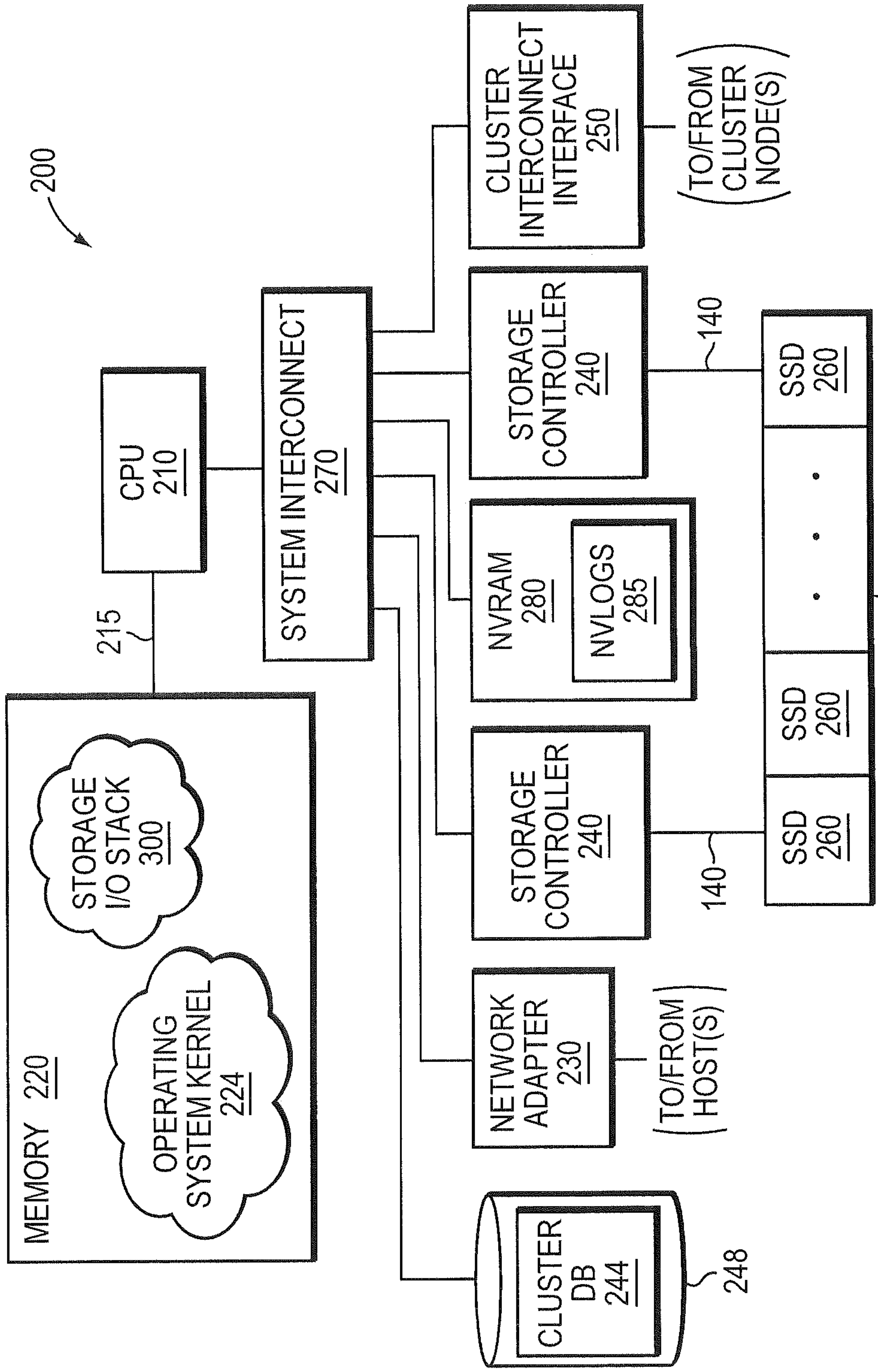

200
CPU
210
215
SYSTEM INTERCONNECT
270
MEMORY 220
STORAGE
I/O STACK
300
OPERATING
SYSTEM KERNEL
224
CLUSTER
INTERCONNECT
INTERFACE
250
TO/FROM
CLUSTER
NODE(S)
STORAGE
CONTROLLER
240
140
NVRAM
280
NVLOGS
285
STORAGE
CONTROLLER
240
140
SSD
260
SSD
260
SSD
260
150
NETWORK
ADAPTER
230
TO/FROM
HOST(S)
CLUSTER
DB
244
248

FIG. 2

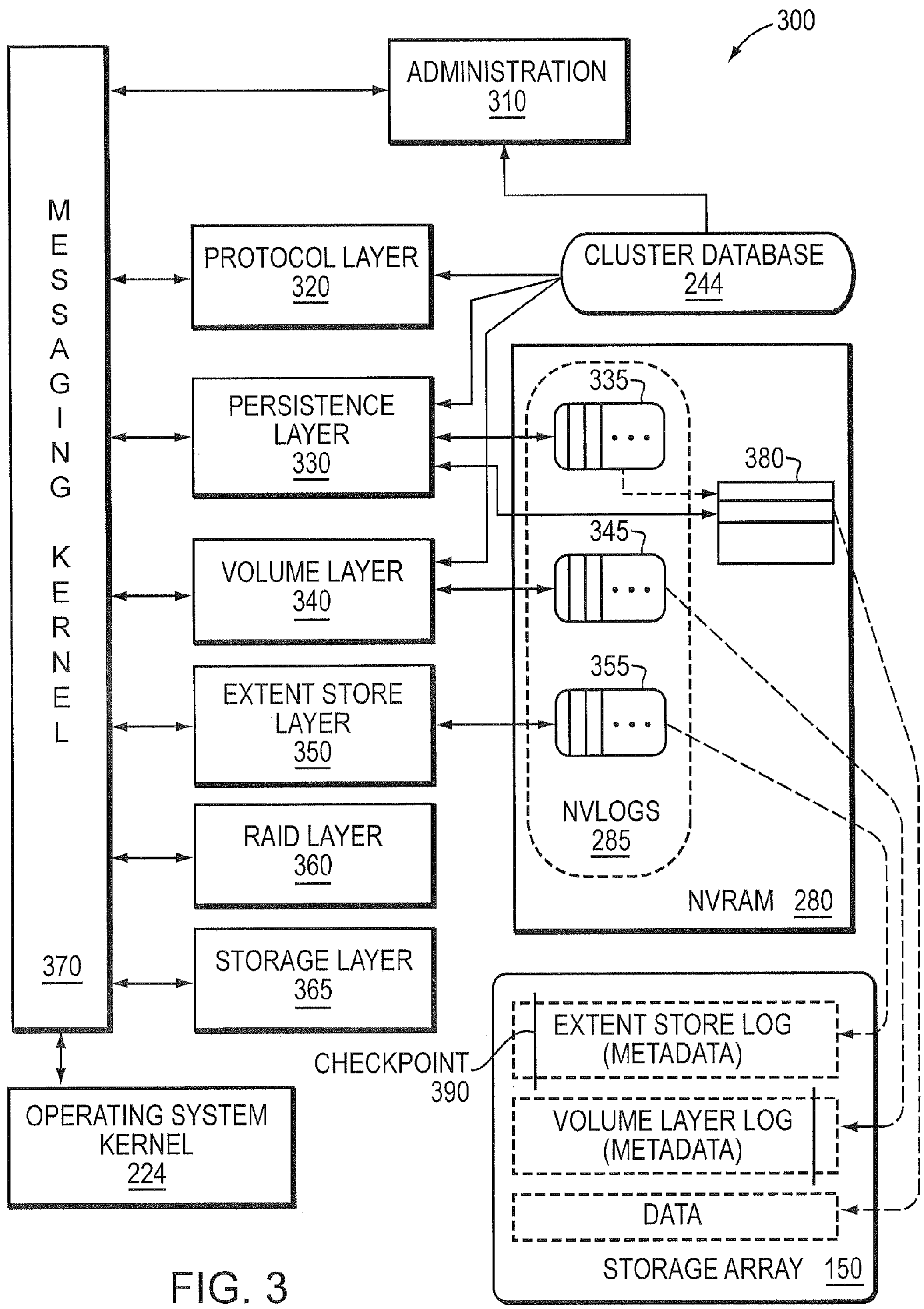

300
ADMINISTRATION
310
MESSAGING KERNEL
370
PROTOCOL LAYER
320
CLUSTER DATABASE
244
PERSISTENCE LAYER
330
335
380
VOLUME LAYER
340
345
EXTENT STORE LAYER
350
355
RAID LAYER
360
NVLOGS
285
NVRAM 280
STORAGE LAYER
365
EXTENT STORE LOG (METADATA)
CHECKPOINT
390
VOLUME LAYER LOG (METADATA)
DATA
STORAGE ARRAY 150
OPERATING SYSTEM KERNEL
224

FIG. 3

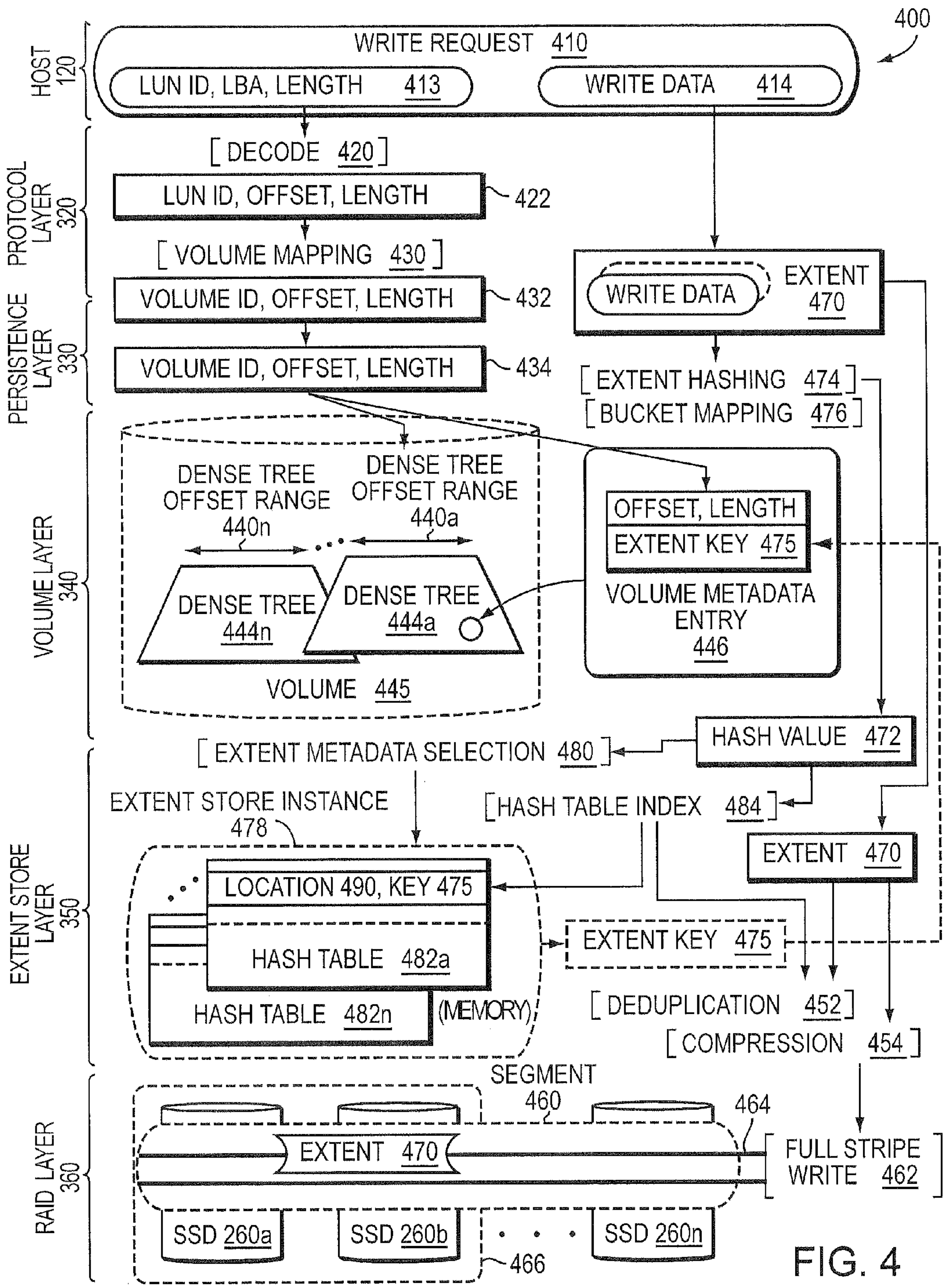
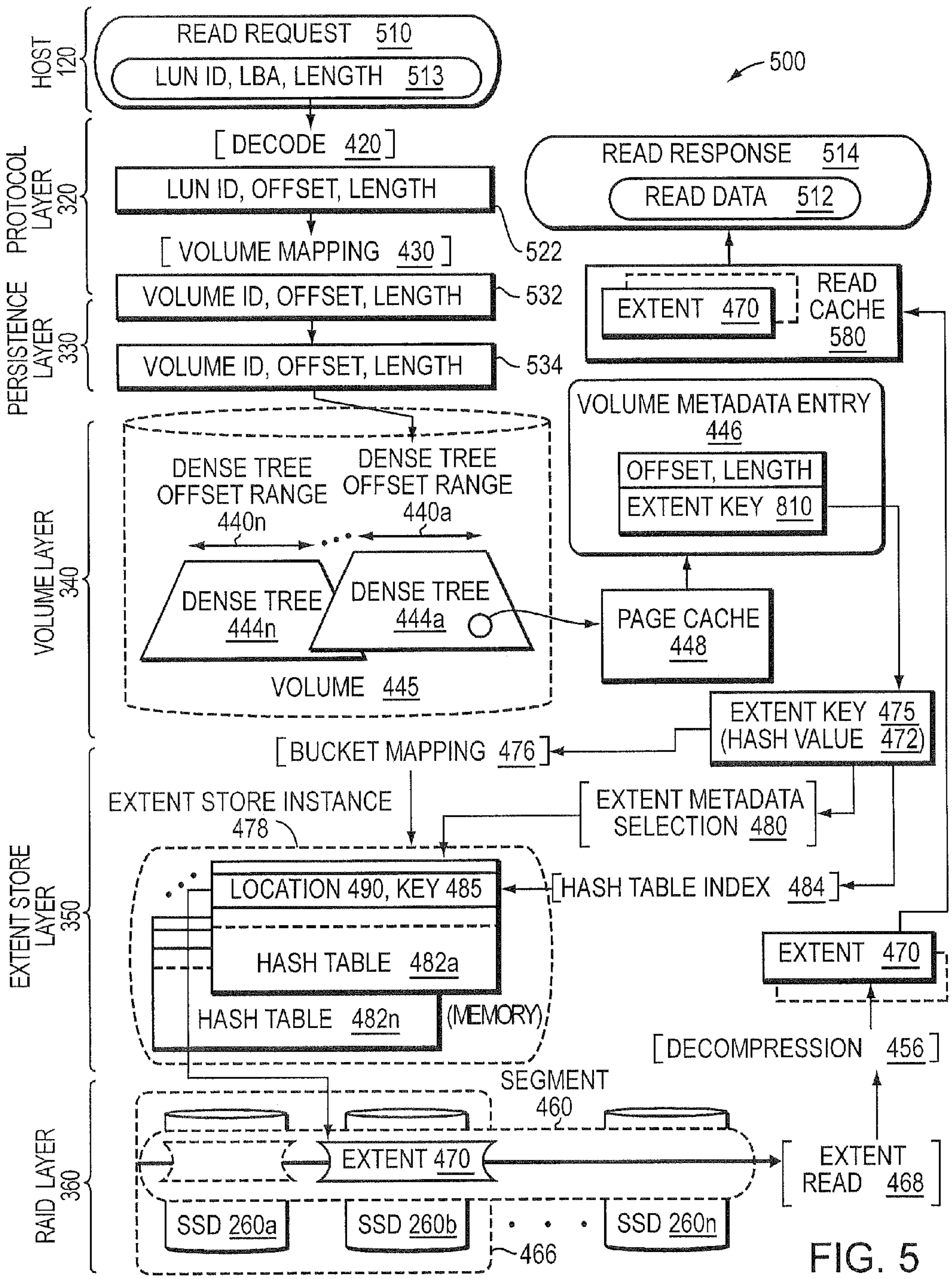
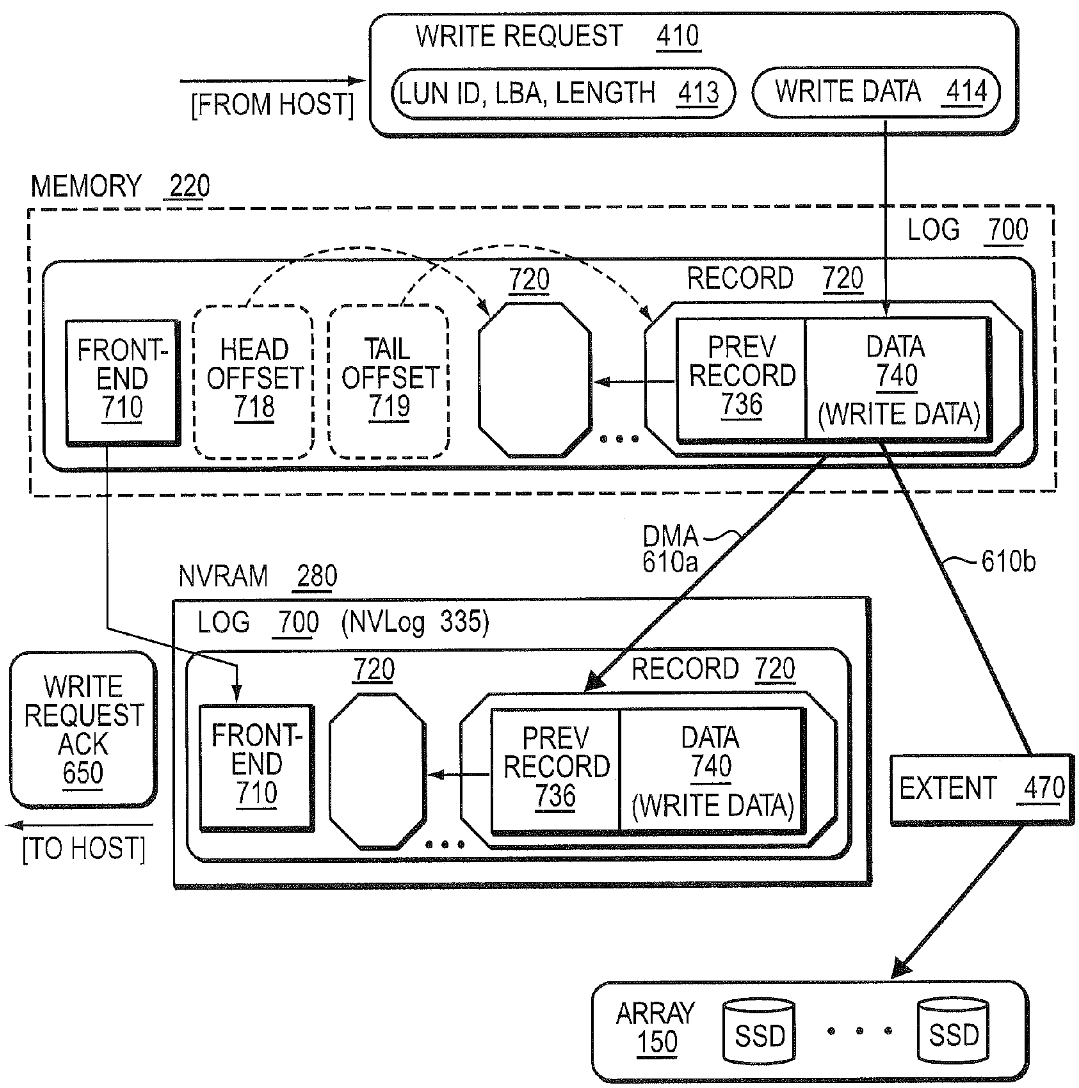

400
HOST 120
WRITE REQUEST 410
LUN ID, LBA, LENGTH 413
WRITE DATA 414
PROTOCOL LAYER 320
DECODE 420
LUN ID, OFFSET, LENGTH
422
VOLUME MAPPING 430
VOLUME ID, OFFSET, LENGTH
432
PERSISTENCE LAYER 330
VOLUME ID, OFFSET, LENGTH
434
WRITE DATA
EXTENT 470
EXTENT HASHING 474
BUCKET MAPPING 476
VOLUME LAYER 340
DENSE TREE OFFSET RANGE 440n
DENSE TREE OFFSET RANGE 440a
DENSE TREE 444n
DENSE TREE 444a
VOLUME 445
OFFSET, LENGTH
EXTENT KEY 475
VOLUME METADATA ENTRY 446
HASH VALUE 472
EXTENT METADATA SELECTION 480
EXTENT STORE LAYER 350
EXTENT STORE INSTANCE 478
HASH TABLE INDEX 484
EXTENT 470
LOCATION 490, KEY 475
HASH TABLE 482a
HASH TABLE 482n
(MEMORY)
EXTENT KEY 475
DEDUPLICATION 452
COMPRESSION 454
RAID LAYER 360
SEGMENT 460
464
EXTENT 470
FULL STRIPE WRITE 462
SSD 260a
SSD 260b
SSD 260n
466

FIG. 4



HOST 120
READ REQUEST 510
LUN ID, LBA, LENGTH 513
500
DECODE 420
PROTOCOL LAYER 320
LUN ID, OFFSET, LENGTH
522
VOLUME MAPPING 430
READ RESPONSE 514
READ DATA 512
PERSISTENCE LAYER 330
VOLUME ID, OFFSET, LENGTH
532
VOLUME ID, OFFSET, LENGTH
534
EXTENT 470
READ CACHE 580
VOLUME METADATA ENTRY 446
OFFSET, LENGTH
EXTENT KEY 810
VOLUME LAYER 340
DENSE TREE OFFSET RANGE 440n
DENSE TREE OFFSET RANGE 440a
DENSE TREE 444n
DENSE TREE 444a
PAGE CACHE 448
VOLUME 445
EXTENT KEY 475
(HASH VALUE 472)
BUCKET MAPPING 476
EXTENT STORE LAYER 350
EXTENT STORE INSTANCE 478
EXTENT METADATA SELECTION 480
LOCATION 490, KEY 485
HASH TABLE INDEX 484
HASH TABLE 482a
HASH TABLE 482n
(MEMORY)
EXTENT 470
DECOMPRESSION 456
SEGMENT 460
RAID LAYER 360
EXTENT 470
EXTENT READ 468
SSD 260a
SSD 260b
SSD 260n
466

FIG. 5



WRITE REQUEST 410
[FROM HOST]
LUN ID, LBA, LENGTH 413
WRITE DATA 414
MEMORY 220
LOG 700
720
RECORD 720
FRONT-END 710
HEAD OFFSET 718
TAIL OFFSET 719
PREV RECORD 736
DATA 740 (WRITE DATA)
DMA 610a
610b
NVRAM 280
LOG 700 (NVLog 335)
720
RECORD 720
WRITE REQUEST ACK 650
[TO HOST]
FRONT-END 710
PREV RECORD 736
DATA 740 (WRITE DATA)
EXTENT 470
ARRAY 150
SSD
SSD

FIG. 6

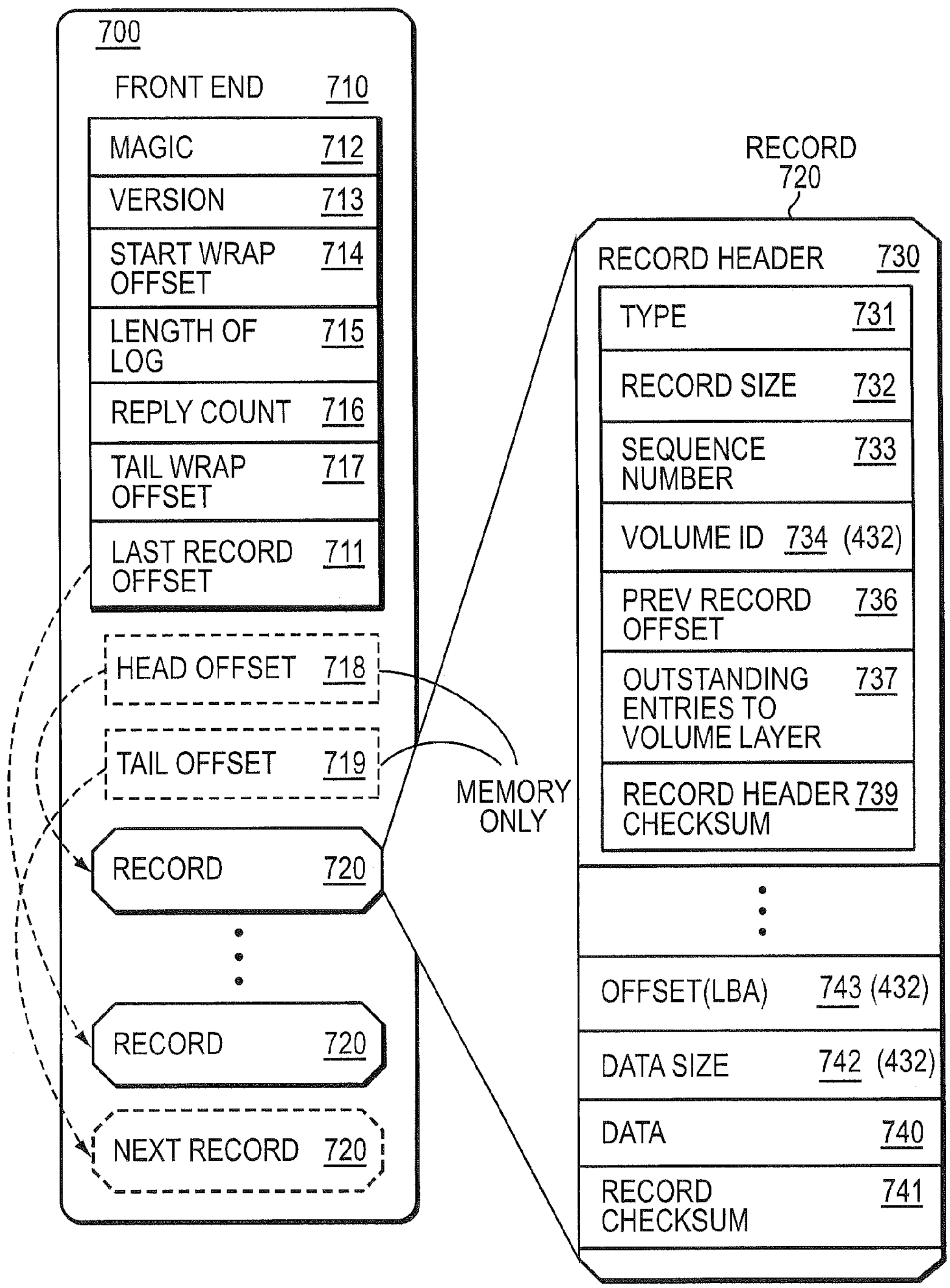

700
FRONT END 710
MAGIC 712
VERSION 713
START WRAP OFFSET 714
LENGTH OF LOG 715
REPLY COUNT 716
TAIL WRAP OFFSET 717
LAST RECORD OFFSET 711
HEAD OFFSET 718
TAIL OFFSET 719
RECORD 720
RECORD 720
NEXT RECORD 720
MEMORY ONLY
RECORD 720
RECORD HEADER 730
TYPE 731
RECORD SIZE 732
SEQUENCE NUMBER 733
VOLUME ID 734 (432)
PREV RECORD OFFSET 736
OUTSTANDING ENTRIES TO VOLUME LAYER 737
RECORD HEADER CHECKSUM 739
OFFSET(LBA) 743 (432)
DATA SIZE 742 (432)
DATA 740
RECORD CHECKSUM 741

FIG. 7A

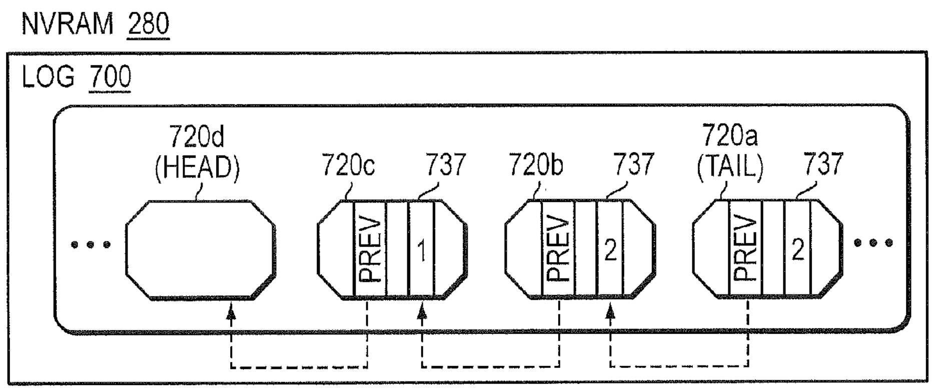

NVRAM 280
LOG 700
720d
(HEAD)
720c
737
720b
737
720a
(TAIL)
737
PREV
1
PREV
2
PREV
2

FIG. 7B

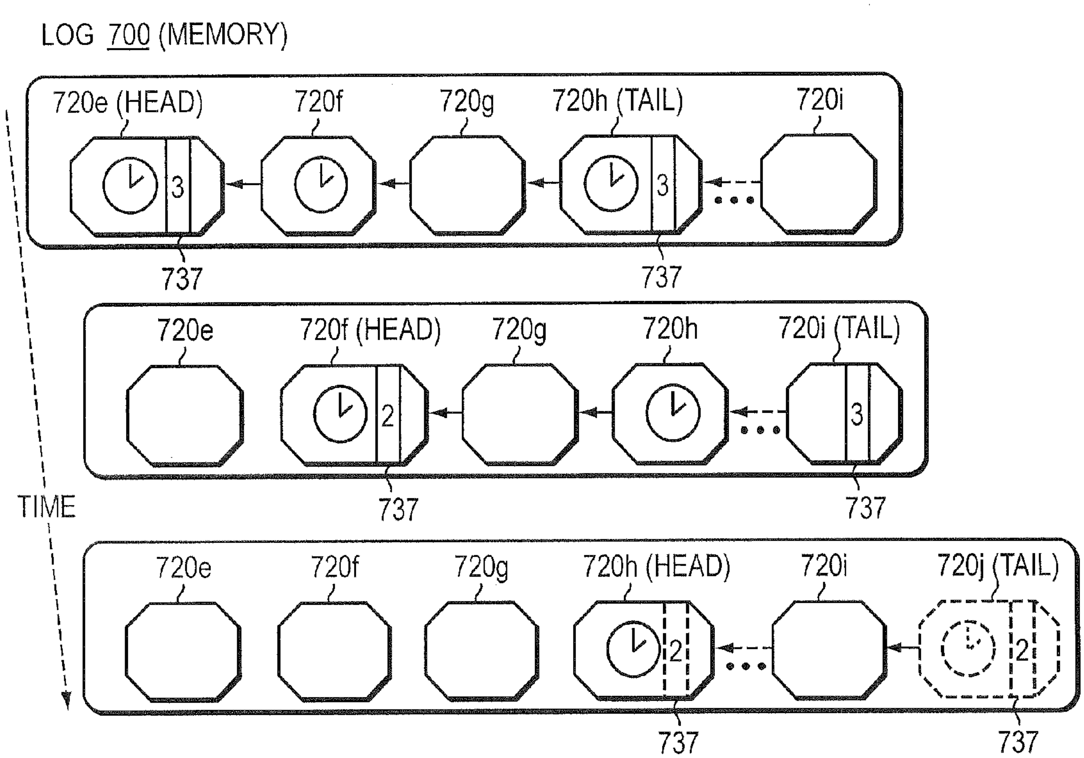

LOG 700 (MEMORY)
720e (HEAD)
720f
720g
720h (TAIL)
720i
3
3
737
737
720e
720f (HEAD)
720g
720h
720i (TAIL)
2
3
737
737
TIME
720e
720f
720g
720h (HEAD)
720i
720j (TAIL)
2
2
737
737

FIG. 7C

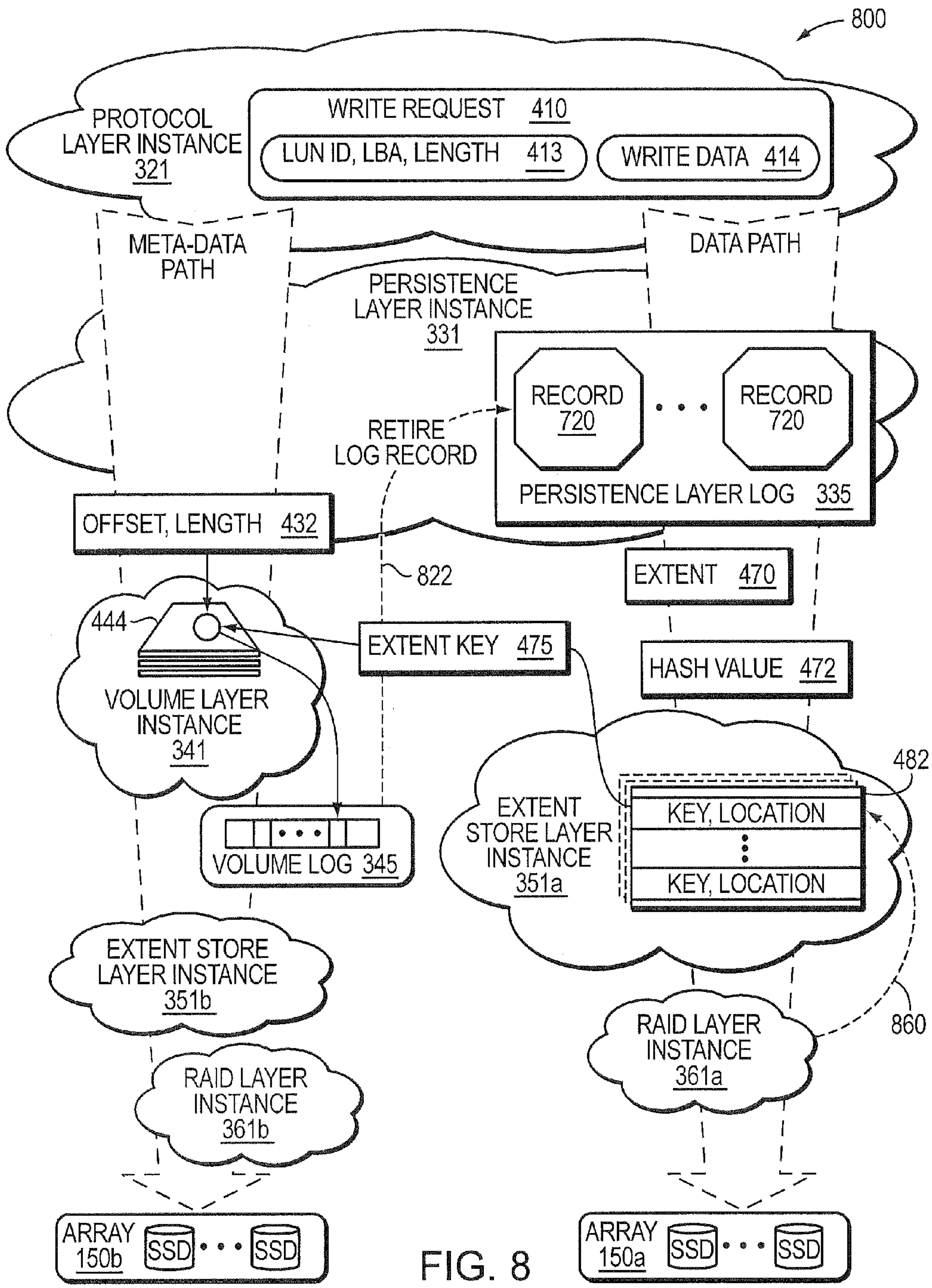

800
PROTOCOL LAYER INSTANCE 321
WRITE REQUEST 410
LUN ID, LBA, LENGTH 413
WRITE DATA 414
META-DATA PATH
DATA PATH
PERSISTENCE LAYER INSTANCE 331
RECORD 720
RECORD 720
RETIRE LOG RECORD
PERSISTENCE LAYER LOG 335
OFFSET, LENGTH 432
EXTENT 470
822
444
EXTENT KEY 475
HASH VALUE 472
VOLUME LAYER INSTANCE 341
482
EXTENT STORE LAYER INSTANCE 351a
KEY, LOCATION
KEY, LOCATION
VOLUME LOG 345
EXTENT STORE LAYER INSTANCE 351b
860
RAID LAYER INSTANCE 361a
RAID LAYER INSTANCE 361b
ARRAY 150b
SSD
SSD
ARRAY 150a
SSD
SSD

FIG. 8

NVRAM DATA ORGANIZATION USING SELF-DESCRIBING ENTITIES FOR PREDICTABLE RECOVERY AFTER POWER-LOSS

BACKGROUND

1. Technical Field

The present disclosure relates to storage systems and, more specifically, to logging of data, including metadata, in non-volatile random access memory (NVRAM) of a storage system.

2. Background

A storage system typically includes one or more storage devices, such as solid state drives (SSDs) embodied as flash storage devices, into which information may be entered, and from which the information may be obtained, as desired. The storage system may logically organize the information stored on the devices as storage containers, such as files or logical units (LUNs). These storage containers may be accessible by a host system using a data protocol over a network connecting the storage system to the host. Each storage container may be implemented as a set of data structures, such as data blocks that store data for the storage containers and metadata blocks that describe the data of the storage containers.

Some types of SSDs, especially those with NAND flash components, move data among those components at the granularity of a page (e.g., 8 kilobytes) and then only to previously erased pages. Typically, pages are erased exclusively in blocks of 32 or more pages (i.e., 256 KB or more). Accordingly, to store data from one or more input/output (I/O) requests, e.g., smaller than a page, an SSD may modify a page, then erase an entire block (e.g., 256 KB) and rewrite the entire block as modified by the data (i.e., less than a page, 8 KB). As a result, storage to SSD may be slow and inefficient, even slower than some traditional magnetic media disk drives. Thus, fast and efficient acknowledgement of the I/O requests by the storage system is desirable so as to reduce latency from the perspective of a host. To that end, some protocols permit data to be stored out-of-order, i.e., in different order to that which I/O requests from the host are received at the storage system.

However, data associated with an I/O request may be lost when power is interrupted on the storage system. This is particularly problematic when the I/O request, e.g., a write request, from the host has been acknowledged by the storage system and write data associated with the request has been sent to the one or more storage devices prior to a power loss, i.e., power is interrupted prior to permanent storage on the device. Recording, e.g., logging, the write request (including write data) to a persistent medium on the storage system and acknowledging the write request to the host reduces the window of storage system vulnerability, i.e., the time during which the storage system cannot guarantee persistent storing of the write request to the data container.

However, recording of the write request (including write data) along with eventual storage of the write data to the data container consumes storage system resources, such as I/O bandwidth. This is particularly acute in high I/O operations per second (TOPS) storage systems where recording each write request may involve multiple metadata accesses to storage which increases latency of write request acknowledgements to the host. Therefore, there is a need to provide low latency for acknowledgement of I/O requests while providing power loss resiliency by persistently logging those I/O requests.

BRIEF DESCRIPTION OF THE DRAWINGS

The above and further advantages of the embodiments herein may be better understood by referring to the following description in conjunction with the accompanying drawings in which like reference numerals indicate identically or functionally similar elements, of which:

FIG. **1** is a block diagram of a plurality of nodes interconnected as a cluster;

FIG. **2** is a block diagram of a node;

FIG. **3** is a block diagram of a storage input/output (I/O) stack of the node;

FIG. **4** illustrates a write path of the storage I/O stack;

FIG. **5** illustrates a read path of the storage I/O stack;

FIG. **6** is a block diagram of logging in a persistence layer of the storage I/O stack;

FIG. **7***a* is a block diagram of the persistence layer log format of the storage I/O stack;

FIG. **7***b*. illustrates replay of the persistence layer log from NVRAM;

FIG. **7***c*. illustrates advancement of the persistence layer log in memory; and

FIG. **8** illustrates data and metadata paths of the storage I/O stack.

DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

The embodiments described herein provide a parallel (e.g., tiered) logging technique configured to deliver low latency acknowledgements of input/output (I/O) requests, such as write requests, while avoiding loss of data associated with the requests that may occur as a result of power failures. Write data associated with one or more write requests may be received at a storage system, which is illustratively embodied as a node of a cluster. The write data may be stored (copied) as a log in a portion of a volatile (dynamic) random access memory (DRAM) and a non-volatile random access memory (NVRAM). The NVRAM may be configured as, e.g., a persistent write-back cache of the node, while parameters of the request may be stored in another portion of the NVRAM configured as the log (NVLog). The write data may be organized into separate variable length blocks or extents and "written back" out-of-order from the write-back cache to storage devices, such as SSDs, e.g., organized into a data container (intended destination of the write request). Illustratively, the storage devices may be consumer grade SSDs serviced by other nodes in the cluster. The write data may be preserved in the NVlog until each extent is safely and successfully stored on SSD (i.e., in the event of power loss) to thereby provide efficient recovery when attempting to restore the write data preserved (persistently) in the NVlog to the data container.

Description

Storage Cluster

FIG. **1** is a block diagram of a plurality of nodes **200** interconnected as a cluster **100** and configured to provide storage service relating to the organization of information on storage devices. The nodes **200** may be interconnected by a cluster interconnect fabric **110** and include functional components that cooperate to provide a distributed storage architecture of the cluster **100**, which may be deployed in a storage area network (SAN). As described herein, the components of each node **200** include hardware and software functionality that enable the node to connect to one or more hosts **120** over a computer network **130**, as well as to one or more storage arrays **150** of storage devices over a storage interconnect **140**, to thereby render the storage service in accordance with the distributed storage architecture.

Each host **120** may be embodied as a general-purpose computer configured to interact with any node **200** in accordance with a client/server model of information delivery. That is, the client (host) may request the services of the node, and the node may return the results of the services requested by the host, by exchanging packets over the network **130**. The host may issue packets including file-based access protocols, such as the Network File System (NFS) protocol over the Transmission Control Protocol/Internet Protocol (TCP/IP), when accessing information on the node in the form of storage containers such as files and directories. However, in an embodiment, the host **120** illustratively issues packets including block-based access protocols, such as the Small Computer Systems Interface (SCSI) protocol encapsulated over TCP (iSCSI) and SCSI encapsulated over FC (FCP), when accessing information in the form of storage containers such as logical units (LUNs). Notably, any of the nodes **200** may service a request directed to a storage container stored on the cluster **100**.

FIG. **2** is a block diagram of a node **200** that is illustratively embodied as a storage system having one or more central processing units (CPUs) **210** coupled to a memory **220** via a memory bus **215**. The CPU **210** is also coupled to a network adapter **230**, storage controllers **240**, a cluster interconnect interface **250** and a non-volatile random access memory (NVRAM **280**) via a system interconnect **270**. The network adapter **230** may include one or more ports adapted to couple the node **200** to the host(s) **120** over computer network **130**, which may include point-to-point links, wide area networks, virtual private networks implemented over a public network (Internet) or a local area network. The network adapter **230** thus includes the mechanical, electrical and signaling circuitry needed to connect the node to the network **130**, which illustratively embodies an Ethernet or Fibre Channel (FC) network.

The memory **220** may include memory locations that are addressable by the CPU **210** for storing software programs and data structures associated with the embodiments described herein. The CPU **210** may, in turn, include processing elements and/or logic circuitry configured to execute the software programs, such as a storage input/output (I/O) stack **300**, and manipulate the data structures. Illustratively, the storage I/O stack **300** may be implemented as a set of user mode processes that may be decomposed into a plurality of threads. An operating system kernel **224**, portions of which are typically resident in memory **220** (in-core) and executed by the processing elements (i.e., CPU **210**), functionally organizes the node by, inter alia, invoking operations in support of the storage service implemented by the node and, in particular, the storage I/O stack **300**. A suitable operating system kernel **224** may include a general-purpose operating system, such as the UNIX® series or Microsoft Windows® series of operating systems, or an operating system with configurable functionality such as microkernels and embedded kernels. However, in an embodiment described herein, the operating system kernel is illustratively the Linux® operating system. It will be apparent to those skilled in the art that other processing and memory means, including various computer readable media, may be used to store and execute program instructions pertaining to the embodiments herein.

Each storage controller **240** cooperates with the storage I/O stack **300** executing on the node **200** to access information requested by the host **120**. The information is preferably stored on storage devices such as solid state drives (SSDs) **260**, illustratively embodied as flash storage devices, of storage array **150**. In an embodiment, the flash storage devices may be based on NAND flash components, e.g., single-layer-cell (SLC) flash, multi-layer-cell (MLC) flash or triple-layer-cell (TLC) flash, although it will be understood to those skilled in the art that other non-volatile, solid-state electronic devices (e.g., drives based on storage class memory components) may be advantageously used with the embodiments described herein. Accordingly, the storage devices may or may not be block-oriented (i.e., accessed as blocks). The storage controller **240** includes one or more ports having I/O interface circuitry that couples to the SSDs **260** over the storage interconnect **140**, illustratively embodied as a serial attached SCSI (SAS) topology. Alternatively, other point-to-point I/O interconnect arrangements, such as a conventional serial ATA (SATA) topology or a PCI topology, may be used. The system interconnect **270** may also couple the node **200** to a local service storage device **248**, such as an SSD configured to locally store cluster-related configuration information, e.g., as cluster database (DB) **244**, which may be replicated to other nodes **200** in the cluster **100**.

The cluster interconnect interface **250** may include one or more ports adapted to couple the node **200** to the other node(s) of the cluster **100**. In an embodiment, Ethernet may be used as the clustering protocol and interconnect fabric media, although it will be apparent to those skilled in the art that other types of protocols and interconnects, such as Infiniband, may be utilized within the embodiments described herein. The NVRAM **280** may include a back-up battery or other built-in last-state retention capability (e.g., non-volatile semiconductor memory such as storage class memory) that is capable of maintaining data in light of a failure to the node and cluster environment. Illustratively, a portion of the NVRAM **280** may be configured as one or more non-volatile logs (NVLogs **285**) configured to temporarily record ("log") I/O requests, such as write requests, received from the host **120**.

Storage I/O Stack

FIG. **3** is a block diagram of the storage I/O stack **300** that may be advantageously used with one or more embodiments described herein. The storage I/O stack **300** includes a plurality of software modules or layers that cooperate with other functional components of the nodes **200** to provide the distributed storage architecture of the cluster **100**. In an embodiment, the distributed storage architecture presents an abstraction of a single storage container, i.e., all of the storage arrays **150** of the nodes **200** for the entire cluster **100** organized as one large pool of storage. In other words, the architecture consolidates storage, i.e., the SSDs **260** of the arrays **150**, throughout the cluster (retrievable via cluster-wide keys) to enable storage of the LUNs. Both storage capacity and performance may then be subsequently scaled by adding nodes **200** to the cluster **100**.

Illustratively, the storage I/O stack **300** includes an administration layer **310**, a protocol layer **320**, a persistence layer **330**, a volume layer **340**, an extent store layer **350**, a Redundant Array of Independent Disks (RAID) layer **360**, a storage layer **365** and a NVRAM (storing NVLogs) "layer" interconnected with a messaging kernel **370**. The messaging kernel **370** may provide a message-based (or event-based) scheduling model (e.g., asynchronous scheduling) that employs messages as fundamental units of work exchanged (i.e., passed) among the layers. Suitable message-passing mechanisms provided by the messaging kernel to transfer information between the layers of the storage I/O stack **300** may include, e.g., for intra-node communication: i) messages that execute on a pool of threads, ii) messages that execute on a single thread progressing as an operation through the storage I/O stack, iii) messages using an Inter Process Communication (IPC) mechanism, and e.g., for inter-node communication: messages using a Remote Procedure Call (RPC) mechanism in accordance with a function shipping implementation. Alternatively, the storage I/O stack **300** may be implemented using a thread-based or stack-based execution model without messages. In one or more embodiments, the messaging kernel **370** allocates processing resources from the operating system kernel **224** to execute the messages. Each storage I/O stack layer may be implemented as one or more instances (i.e., processes) executing one or more threads (e.g., in kernel or user space) that process the messages passed between the layers such that the messages provide synchronization for blocking and non-blocking operation of the layers.

In an embodiment, the protocol layer **320** may communicate with the host **120** over the network **130** by exchanging discrete frames or packets configured as I/O requests according to pre-defined protocols, such as iSCSI and FCP. An I/O request, e.g., a read or write request, may be directed to a LUN and may include I/O parameters such as, inter alia, a LUN identifier (ID), a logical block address (LBA) of the LUN, a length (i.e., amount of data) and, in the case of a write request, write data. The protocol layer **320** receives the I/O request and forwards it to the persistence layer **330**, which records the request into a persistent write-back cache **380**, illustratively embodied as a log whose contents can be replaced randomly, e.g., under some random access replacement policy rather than only in serial fashion, and returns an acknowledgement to the host **120** via the protocol layer **320**. In one or more embodiments, only I/O requests that modify the LUN, e.g., write requests, are logged. Notably, the I/O request may be logged at the node receiving the I/O request, or in an alternative embodiment in accordance with the function shipping implementation, the I/O request may be logged at another node.

Illustratively, dedicated logs may be maintained by the various layers of the storage I/O stack **300**. For example, a dedicated log **335** may be maintained by the persistence layer **330** to record the I/O parameters of an I/O request as equivalent internal, i.e., storage I/O stack, parameters, e.g., volume ID, offset, and length. In the case of a write request, the persistence layer **330** may also cooperate with the NVRAM **280** to implement the write-back cache **380** configured to store the write data associated with the write request. In an embodiment, the write-back cache may be structured as a log. Notably, the write data for the write request may be physically stored in the cache **380** such that the log **335** contains the reference to the associated write data. It will be understood to persons skilled in the art that other variations of data structures may be used to store or maintain the write data in NVRAM including data structures with no logs. In an embodiment, a copy of the write-back cache may also be maintained in the memory **220** to facilitate direct memory access to the storage controllers. In other embodiments, caching may be performed at the host **120** or at a receiving node in accordance with a protocol that maintains coherency between the write data stored at the cache and the cluster.

In an embodiment, the administration layer **310** may apportion the LUN into multiple volumes, each of which may be partitioned into multiple regions (e.g., allotted as disjoint block address ranges), with each region having one or more segments stored as multiple stripes on the array **150**. A plurality of volumes distributed among the nodes **200** may thus service a single LUN, i.e., each volume within the LUN services a different LBA range (i.e., offset and length, hereinafter offset range) or set of ranges within the LUN. The protocol layer **320** may implement a volume mapping technique to identify a volume to which the I/O request is directed (i.e., the volume servicing the offset range indicated by the parameters of the I/O request). Illustratively, the cluster database **244** may be configured to maintain one or more associations (e.g., key-value pairs) for each of the multiple volumes, e.g., an association between the LUN ID and a volume, as well as an association between the volume and a node ID for a node managing the volume. The administration layer **310** may also cooperate with the database **244** to create (or delete) one or more volumes associated with the LUN (e.g., creating a volume ID/LUN key-value pair in the database **244**). Using the LUN ID and LBA (or LBA range), the volume mapping technique may provide a volume ID (e.g., using appropriate associations in the cluster database **244**) that identifies the volume and node servicing the volume destined for the request, as well as translate the LBA (or LBA range) into an offset and length within the volume. Specifically, the volume ID is used to determine a volume layer instance that manages volume metadata associated with the LBA or LBA range. As noted, the protocol layer **320** may pass the I/O request (i.e., volume ID, offset and length) to the persistence layer **330**, which may use the function shipping (e.g., inter-node) implementation to forward the I/O request to the appropriate volume layer instance executing on a node in the cluster based on the volume ID.

In an embodiment, the volume layer **340** may manage the volume metadata by, e.g., maintaining states of host-visible containers, such as ranges of LUNs, and performing data management functions, such as creation of snapshots and clones, for the LUNs in cooperation with the administration layer **310**. The volume metadata is illustratively embodied as in-core mappings from LUN addresses (i.e., LBAs) to durable extent keys, which are unique cluster-wide IDs associated with SSD storage locations for extents within an extent key space of the cluster-wide storage container. That is, an extent key may be used to retrieve the data of the extent at an SSD storage location associated with the extent key. Alternatively, there may be multiple storage containers in the cluster wherein each container has its own extent key space, e.g., where the administration layer **310** provides distribution of extents among the storage containers. Illustratively, an extent is a variable length block of data that provides a unit of storage on the SSDs that need not be aligned on any specific boundary, i.e., it may be byte aligned. Accordingly, an extent may be an aggregation of write data from a plurality of write requests to maintain such alignment. Illustratively, the volume layer **340** may record the forwarded request (e.g., information or parameters characterizing the request), as well as changes to the volume metadata, in dedicated log **345** maintained by the volume layer. Subsequently, the contents of the volume layer log **345** may be written to the storage array **150** in accordance with retirement of log entries, while a checkpoint (e.g., synchronization) operation that stores in-core metadata on the array **150**. That is, the checkpoint operation (checkpoint) ensures that a consistent state of metadata, as processed in-core, is committed to (i.e., stored on) the storage array **150**; whereas the retirement of log entries ensures that the entries accumulated in the volume layer log **345** synchronize with the metadata checkpoints committed to the storage array **150** by, e.g., retiring those accumulated log entries that are prior to the checkpoint. In one or more embodiments, the checkpoint and retirement of log entries may be data driven, periodic or both.

In an embodiment, the extent store layer **350** is responsible for storing extents on the SSDs **260** (i.e., on the storage array **150**) and for providing the extent keys to the volume layer **340** (e.g., in response to a forwarded write request). The extent store layer **350** is also responsible for retrieving data (e.g., an existing extent) using an extent key (e.g., in response to a forwarded read request). The extent store layer **350** may be responsible for performing de-duplication and compression on the extents prior to storage. The extent store layer **350** may maintain in-core mappings (e.g., embodied as hash tables) of extent keys to SSD storage locations (e.g., offset on an SSD **260** of array **150**). The extent store layer **350** may also maintain a dedicated log **355** of entries that accumulate requested "put" and "delete" operations (i.e., write requests and delete requests for extents issued from other layers to the extent store layer **350**), where these operations change the in-core mappings (i.e., hash table entries). Subsequently, the in-core mappings and contents of the extent store layer log **355** may be written to the storage array **150** in accordance with a "fuzzy" checkpoint **390** (i.e., checkpoints with incremental changes recorded in one or more log files) in which selected in-core mappings, less than the total, are committed to the array **150** at various intervals (e.g., driven by an amount of change to the in-core mappings, size thresholds of log **355**, or periodically). Notably, the accumulated entries in log **355** may be retired once all in-core mappings have been committed to include the changes recorded in those entries.

In an embodiment, the RAID layer **360** may organize the SSDs **260** within the storage array **150** as one or more RAID groups (e.g., sets of SSDs) that enhance the reliability and integrity of extent storage on the array by writing data "stripes" having redundant information, i.e., appropriate parity information with respect to the striped data, across a given number of SSDs **260** of each RAID group. The RAID layer **360** may also store a number of stripes (e.g., stripes of sufficient depth), e.g., in accordance with a plurality of contiguous range write operations, so as to reduce data relocation (i.e., internal flash block management) that may occur within the SSDs as a result of the operations. In an embodiment, the storage layer **365** implements storage I/O drivers that may communicate directly with hardware (e.g., the storage controllers **240** and cluster interface **250**) cooperating with the operating system kernel **224**, such as a Linux virtual function I/O (VFIO) driver.

Write Path

FIG. **4** illustrates an I/O (e.g., write) path **400** of the storage I/O stack **300** for processing an I/O request, e.g., a SCSI write request **410**. The write request **410** may be issued by host **120** and directed to a LUN stored on the storage array **150** of the cluster **100**. Illustratively, the protocol layer **320** receives and processes the write request by decoding **420** (e.g., parsing and extracting) fields of the request, e.g., LUN ID, LBA and length (shown at **413**), as well as write data **414**. The protocol layer **320** may use the results **422** from decoding **420** for a volume mapping technique **430** (described above) that translates the LUN ID and LBA range (i.e., equivalent offset and length) of the write request to an appropriate volume layer instance, i.e., volume ID (volume **445**), in the cluster **100** that is responsible for managing volume metadata for the LBA range. In an alternative embodiment, the persistence layer **330** may implement the above-described volume mapping technique **430**. The protocol layer then passes the results **432**, e.g., volume ID, offset, length (as well as write data), to the persistence layer **330**, which records the request in the persistence layer log **335** and returns an acknowledgement to the host **120** via the protocol layer **320**. The persistence layer **330** may aggregate and organize write data **414** from one or more write requests into a new extent **470** and perform a hash computation, i.e., a hash function, on the new extent to generate a hash value **472** in accordance with an extent hashing technique **474**.

The persistence layer **330** may then pass the write request with aggregated write data including, e.g., the volume ID, offset and length, as parameters **434** to the appropriate volume layer instance. In an embodiment, message passing of the parameters **432** (received by the persistence layer) may be redirected to another node via the function shipping mechanism, e.g., RPC, for inter-node communication. Alternatively, message passing of the parameters **434** may be via the IPC mechanism, e.g., message threads, for intra-node communication.

In one or more embodiments, a bucket mapping technique **476** is provided that translates the hash value **472** to an instance of an appropriate extent store layer (e.g., extent store instance **478**) that is responsible for storing the new extent **470**. Note, the bucket mapping technique may be implemented in any layer of the storage I/O stack **300** above the extent store layer **350**. In an embodiment, for example, the bucket mapping technique may be implemented in the persistence layer **330**, the volume layer **340**, or a layer that manages cluster-wide information, such as a cluster layer (not shown). The persistence layer **330** may then pass the hash value **472** and the new extent **470** to the appropriate volume layer instance and onto the appropriate extent store instance via an extent store put operation. The extent hashing technique **474** may embody an approximately uniform hash function to ensure that any random extent to be written may have an approximately equal chance of falling into any extent store instance **478**, i.e., hash buckets are distributed across extent store instances of the cluster **100** based on available resources. As a result, the bucket mapping technique **476** provides load-balancing of write operations (and, by symmetry, read operations) across nodes **200** of the cluster, while also leveling flash wear in the SSDs **260** of the cluster.

In response to the put operation, the extent store instance may process the hash value **472** to perform an extent metadata selection technique **480** that (i) selects an appropriate hash table **482** (e.g., hash table **482***a*) from a set of hash tables (illustratively in-core) within the extent store instance **478**, and (ii) extracts a hash table index **484** from the hash value **472** to index into the selected hash table and lookup a table entry having an extent key **475** identifying a storage location **490** on SSD **260** for the extent. Accordingly, the extent store layer **350** may contain computer executable instructions executed by the CPU **210** to perform operations that implement the metadata selection technique **480** described herein. If a table entry with a matching key is found, the SSD location **490** mapped from the extent key **475** is used to retrieve an existing extent (not shown) from SSD. The existing extent is then compared with the new extent **470** to determine whether their data is identical. If the data is identical, the new extent **470** is already stored on SSD **260** and a de-duplication opportunity (denoted de-duplication **452**) exists such that there is no need to write another copy of the data. Accordingly, a reference count (not shown) in the table entry for the existing extent is incremented and the extent key **475** of the existing extent is passed to the appropriate volume layer instance for storage within an entry (denoted as volume metadata entry **446**) of a dense tree metadata structure (e.g., dense tree **444***a*), such that the extent key **475** is associated an offset range (e.g., offset range **440***a*) of the volume **445**.

However, if the data of the existing extent is not identical to the data of the new extent **470**, a collision occurs and a deterministic algorithm is invoked to sequentially generate as many new candidate extent keys (not shown) mapping to the same bucket as needed to either provide de-duplication **452** or produce an extent key that is not already stored within the extent store instance. Notably, another hash table (e.g. hash table **482***n*) of extent store instance **478** may be selected by a new candidate extent key in accordance with the extent metadata selection technique **480**. In the event that no de-duplication opportunity exists (i.e., the extent is not already stored) the new extent **470** is compressed in accordance with compression technique **454** and passed to the RAID layer **360**, which processes the new extent **470** for storage on SSD **260** within one or more stripes **464** of RAID group **466**. The extent store instance may cooperate with the RAID layer **360** to identify a storage segment **460** (i.e., a portion of the storage array **150**) and a location on SSD **260** within the segment **460** in which to store the new extent **470**. Illustratively, the identified storage segment is a segment with a large contiguous free space having, e.g., location **490** on SSD **260***b* for storing the extent **470**.

In an embodiment, the RAID layer **360** then writes the stripes **464** across the RAID group **466**, illustratively as a full write stripe **462**. The RAID layer **360** may write a series of stripes **464** of sufficient depth to reduce data relocation that may occur within flash-based SSDs **260** (i.e., flash block management). The extent store instance then (i) loads the SSD location **490** of the new extent **470** into the selected hash table **482***n* (i.e., as selected by the new candidate extent key), (ii) passes a new extent key (denoted as extent key **475**) to the appropriate volume layer instance for storage within an entry (also denoted as volume metadata entry **446**) of a dense tree **444** managed by that volume layer instance, and (iii) records a change to metadata of the selected hash table in the extent store layer log **355**. Illustratively, the volume layer instance selects dense tree **444***a* spanning an offset range **440***a* of the volume **445** that encompasses the offset range of the write request. As noted, the volume **445** (e.g., an offset space of the volume) is partitioned into multiple regions (e.g., allotted as disjoint offset ranges); in an embodiment, each region is represented by a dense tree **444**. The volume layer instance then inserts the volume metadata entry **446** into the dense tree **444***a* and records a change corresponding to the volume metadata entry in the volume layer log **345**. Accordingly, the I/O (write) request is sufficiently stored on SSD **260** of the cluster.

Read Path

FIG. **5** illustrates an I/O (e.g., read) path **500** of the storage I/O stack **300** for processing an I/O request, e.g., a SCSI read request **510**. The read request **510** may be issued by host **120** and received at the protocol layer **320** of a node **200** in the cluster **100**. Illustratively, the protocol layer **320** processes the read request by decoding **420** (e.g., parsing and extracting) fields of the request, e.g., LUN ID, LBA, and length (shown at **513**), and uses the results **522**, e.g., LUN ID, offset, and length, for the volume mapping technique. That is, the protocol layer **320** may implement the volume mapping technique **430** (described above) to translate the LUN ID and LBA range (i.e., equivalent offset and length) of the read request to an appropriate volume layer instance, i.e., volume ID (volume **445**), in the cluster **100** that is responsible for managing volume metadata for the LBA (i.e., offset) range. The protocol layer then passes the results **532** to the persistence layer **330**, which may search the write-back cache **380** to determine whether some or all of the read request can be serviced from its cached data. If the entire request cannot be serviced from the cached data, the persistence layer **330** may then pass the remaining portion of the request including, e.g., the volume ID, offset and length, as parameters **534** to the appropriate volume layer instance in accordance with the function shipping mechanism (e.g., RPC, for inter-node communication) or the IPC mechanism (e.g., message threads, for intra-node communication).

The volume layer instance may process the read request to access a dense tree metadata structure (e.g., dense tree **444***a*) associated with a region (e.g., offset range **440***a*) of a volume **445** that encompasses the requested offset range (specified by parameters **534**). The volume layer instance may further process the read request to search for (lookup) one or more volume metadata entries **446** of the dense tree **444***a* to obtain one or more extent keys **475** associated with one or more extents **470** within the requested offset range. Illustratively, each dense tree **444** may be embodied as a-multiple levels of a search structure with possibly overlapping offset range entries at each level. The entries, i.e., volume metadata entries **446**, provide mappings from host-accessible LUN addresses, i.e., LBAs (offsets), to durable extent keys. The various levels of the dense tree may have volume metadata entries **446** for the same offset, in which case the higher level has the newer entry and is used to service the read request. A top level of the dense tree **444** is illustratively resident in-core and a page cache **448** may be used to access lower levels of the tree. If the requested range or portion thereof is not present in the top level, a metadata page associated with an index entry at the next lower tree level is accessed. The metadata page (i.e., in the page cache **448**) at the next level is then searched (e.g., a binary search) to find any overlapping entries. This process is then iterated until one or more volume metadata entries **446** of a level are found to ensure that the extent key(s) **475** for the entire requested read range are found. If no metadata entries exist for the entire or portions of the requested read range, then the missing portion(s) are zero filled.

Once found, each extent key **475** is processed by the volume layer **340** to, e.g., implement the bucket mapping technique **476** that translates the extent key to an appropriate extent store instance **478** responsible for storing the requested extent **470**. Note that, in an embodiment, each extent key **475** may be substantially identical to the hash value **472** associated with the extent **470**, i.e., the hash value as calculated during the write request for the extent, such that the bucket mapping **476** and extent metadata selection **480** techniques may be used for both write and read path operations. Note also that the extent key **475** may be derived from the hash value **472**. The volume layer **340** may then pass the extent key **475** (i.e., the hash value from a previous write request for the extent) to the appropriate extent store instance **478** (via an extent store get operation), which performs an extent key-to-SSD mapping to determine the location on SSD **260** for the extent.

In response to the get operation, the extent store instance may process the extent key **475** (i.e., the hash value **472**) to perform the extent metadata selection technique **480** that (i) selects an appropriate hash table (e.g., hash table **482***a*) from a set of hash tables within the extent store instance **478**, and (ii) extracts a hash table index **484** from the extent key **475** (i.e., the hash value **472**) to index into the selected hash table and lookup a table entry having a matching extent key **475** that identifies a storage location **490** on SSD **260** for the extent **470**. That is, the SSD location **490** mapped to the extent key **475** may be used to retrieve the existing extent (denoted as extent **470**) from SSD **260** (e.g., SSD **260***b*). The extent store instance then cooperates with the RAID layer **360** to access the extent on SSD **260***b* and retrieve the data contents in accordance with the read request. Illustratively, the RAID layer **360** may read the extent in accordance with an extent read operation **468** and pass the extent **470** to the extent store instance. The extent store instance may then decompress the extent **470** in accordance with a decompression technique **456**, although it will be understood to those skilled in the art that decompression can be performed at any layer of the storage I/O stack **300**. The extent **470** may be stored in a buffer (not shown) in memory **220** and a reference to that buffer may be passed back through the layers of the storage I/O stack. The persistence layer may then load the extent into a read cache **580** (or other staging mechanism) and may extract appropriate read data **512** from the read cache **580** for the LBA range of the read request **510**. Thereafter, the protocol layer **320** may create a SCSI read response **514**, including the read data **512**, and return the read response to the host **120**.

Parallel Logging

As noted, a write request **410** (along with write data **414**) received at the persistence layer **330** is illustratively recorded in the NVLogs **285** (i.e., persistent layer log **335**). To that end, the persistence layer **330** may cooperate with the NVRAM to employ a log for recording an I/O request **410** issued by the host **120**. Illustratively, the persistence layer **330** may cooperate with the NVRAM **280** to hide latencies associated with underlying operations (e.g., data and metadata path operations) within the storage I/O stack **300**. Storage of write data **414** in the NVRAM **280** enables immediate, i.e., low latency, acknowledgement to the host **120** of successful receipt and storage of the write data on the cluster **100**. The write data **414** may be stored in NVRAM in the form of a log, e.g., dedicated log **335** of NVLogs **285**. In an embodiment, the write data may also be illustratively organized in the NVRAM in the form of the persistent write-back cache **380**, which may be organized as pointers to write data stored in the log **335**. The write data **414** is thereafter preserved in the NVRAM until written to the storage array **150** (i.e., to the data container) according to a "write-back" operation (as opposed to a checkpoint). Thus, the storage I/O stack **300** need not checkpoint write data; it need only write-back the data to SSD.

Illustratively, storage of the write data **414** to the data container (i.e., the "write-back" operation) may be performed "lazily" (i.e., delayed) depending on the size of the persistence layer log, e.g., in NVRAM. That is, storage of the write data **414** to the data container (i.e., in an extent store) may be delayed, so long as the persistent layer log has capacity to log (i.e., record) incoming write requests which are acknowledged to the host. In an embodiment, a persistent layer log capacity threshold (not shown) may be used to trigger write-back operations which drain the log (i.e., retire log records). Note that when the persistence layer log is full, write requests cannot be safely acknowledged.

Advantageously, use of the persistent write-back cache **380** within the storage I/O stack **300** enables flexibility of how the data is written back to SSD **260**, as opposed to a log which typically compels write-back in approximately the same order in which the write requests were received. For example, if the write data **414** were stored in the persistence layer log **335**, the persistence layer **330** may be compelled to "write-back", i.e., push or copy, the write data to the volume layer **340** in approximately the same order in which the write requests were received to allow reuse of the log space. This is because log space is typically allocated, filled, and freed sequentially, whereas lines within a persistent write-back cache **380** may be allocated, filled, written-back, and freed in any pattern or order convenient to the storage system. Accordingly, a property of the persistent write-back cache **380** of the storage I/O stack **300** is that write data is generally not retired from the cache until the persistence layer **330** receives confirmation (e.g., from the extent store layer **350**) that the write data (extent) is successfully stored on SSD **260** of the storage array.

FIG. **6** is a block diagram of logging in the persistence layer of the storage I/O stack. Illustratively, a write request **410** is received from the host **120** having parameters **413** (i.e., directing the write request to a storage container on the cluster) and write data **414**. The write request is recorded (i.e., logged) in a log **700** stored in the memory **220**, e.g., dynamic random access memory (DRAM). In an embodiment, the log may be organized as a data structure having a front-end **710** and a set of records **720** with metadata such as a head pointer (i.e., head offset **718**) referencing an initial record **720** and a tail pointer (i.e., tail offset **719**) referencing a final record **720** (i.e., last record logged)(see FIG. **7**). Each record may include write data from an I/O request (i.e., data **740**) and a previous record pointer (i.e., prev record offset **736**) referencing the previously logged record. The front-end **710** and each log record may be copied to a persistent storage medium (i.e., NVRAM) by a direct memory access (DMA) operation **610**, such as via the system interconnect **270** using DMA capabilities of the CPU **210**. Notably, the front-end of the log may be substantially copied (e.g., via DMA) to the NVlog **335** (in NVRAM) with the exception of the head offset **718** and tail offset **719**. Illustratively, the CPU, system interconnect **270** and NVRAM **280** have limited bandwidth, therefore it is desirable to reduce the number and duration of DMA operations **610***a-b*. This may be realized by eliminating copying (i.e., updating) the head offset **718** and tail offset **719** from the memory **220** to the NVRAM **280** when log records **720** are created and the log is advanced. That is, DMA operations need only copy log records from memory to NVRAM and avoid DMA operations that copy the head offset and tail offset. As such, an amount of information (e.g., log metadata) copied by DMA may be reduced and contiguous memory DMA operations may be performed (i.e., avoiding overhead of disjointed DMA scatter/gather lists). Accordingly, in an embodiment, head offset **718** and tail offset **719** pointers are only stored in memory **220**, i.e., not stored to NVRAM. Moreover, a single DMA operation **610***a* may be used to copy a contiguous record **720** from memory to NVRAM (NVlog **335**). While another DMA operation **610***b* may be used to copy the data **740** of the log record **720** as one or more extents **470** to the storage array **150**.

Logging Data Structure

FIG. **7***a* is a block diagram of a persistence layer log format **700** that may be advantageously used with one or more embodiments described herein. Illustratively, the log format **700** may be employed in a dedicated log of the NVLogs **285**, which provides an exemplary embodiment of the persistence layer log **335**. Alternatively, the persistence layer log format may be employed solely in NVRAM.

In an embodiment, the log format **700** is illustratively organized as a circular log of records or entries **720** with the front-end **710** (metadata) having a magic number **712** that identifies the log data structure (i.e., enables detection of memory corruption), a version **713** that stores a version of the log, a head offset (pointer) **718** configured to point to (reference) a head entry (i.e., record) at a beginning of the circular log, and a tail offset (pointer) **719** configured to reference a tail entry at an end of the circular log. A last record offset **711** is included to indicate (i.e., reference) the last entry (i.e., the latest entry recorded). The log format **700** also includes a tail wrap offset **717** indicating a location of the end offset of the last (i.e., logical tail) entry when the circular log wraps. Similarly, the log format includes a start wrap offset **714** indicating a location of the beginning of the log when the log wraps. Notably, the tail wrap offset **717** and start wrap offset **714** may be stored to NVRAM (unlike the head offset **718** and the tail offset **719**). Each of these offsets may be used when the circular log wraps. For a log of sufficient size, e.g., greater than 100 entries, wrapping of the log may be infrequent (e.g., 1 out of 100 write requests **410**), thus any additional DMA operations required to writing the tail wrap offset and head wrap offset is small (e.g., 1%).

Illustratively, the log format may further include a replay count **716** indicating a number of times a replay of the log was attempted, e.g. during recovery. After a power loss, acknowledged write requests **410** (i.e., write requests for which the host **120** has received an acknowledgement and, thus, believes are stored by the cluster) may be recovered by replaying the log stored in NVRAM in reverse sequential, e.g., temporal, order using the prev record offset **736** in each entry to traverse the log. A tail (i.e., logical end) of the log in NVRAM may be found by determining the last (i.e., latest written) log entry using a sequence number **733** in each entry, i.e., the sequence number **733** may be used to indicate a temporal order. Illustratively, the log **700** in NVRAM (NVlog **335**) may be scanned record by record. When the sequence number **733** of an entry referenced by the prev record offset **736** (in a current entry) is out of sequence with the sequence number in the current entry, the tail (i.e., latest entry) of the log is found. Replay of the log may be performed by playing back a number of entries whose I/O operations were pending in the other layers of the storage I/O stack at the time the latest entry (i.e., tail entry) was recorded. Notably, the head offset **718** and tail offset **719** (absent from the NVRAM, as indicated above) are not required; the log may be scanned to find the end of the log while (along the way) each entry is verified using a record header checksum **739** (verifying metadata in a record header **730**) and a record checksum **741** (verifying all information in the record) included in each entry. In an embodiment, the log is of sufficiently small size (e.g., less than 10,000 entries), so that scanning the log may be accomplished quickly.

Each entry **720** may have a header **730** further including, inter alia, a type **731** of I/O request (e.g. write request), a record size **732** of the entry and the sequence number **733**. Illustratively, the sequence number **733** (e.g., a monotonically increasing value) facilitates matching of entries within the log **700** to allow retirement (and reclaim) of the entries when all write data associated with the request is safely stored on the storage array **150**. In an embodiment, the sequence number **733** may be a time-stamp or other value that is advantageously employed when the write data is split into multiple extents **470** and written to the storage array out-of-order. Notably, an entry **720** may be retired when all extents associated with the write data **414** of the write request **410** have been successfully stored on SSD **260** of the array **150**. The entry **720** may also include a volume ID **734** (i.e., from parameters **432**) that identifies a volume destined for the request (and a node servicing the volume), an offset **743** (parameters **432**) that identifies an offset (i.e., LBA) for the write data, and a data size **742** (i.e., length from parameters **432**). The record (i.e., entry) size **732** may be provided to calculate the start of the next log entry and a record header checksum **739** may be provided to ensure that the metadata information of the entry is stored without error. The record checksum **741** may also be provided to ensure the integrity of the entire record, i.e., the record header **730** and the variable length data **740** (i.e., write data). In addition, each entry may include an "outstanding entries to volume layer **737**", which is a field indicating the number of write requests (i.e., extents) in-progress (i.e., outstanding) by the volume layer **340**. The outstanding entries to volume layer may be embodied as a counter that tracks the number of log entries (e.g., extents) being processed by lower layers in the storage I/O stack (i.e., volume layer and extent store layer). That is, for each put operation of user data to the volume layer **340** (subsequently to the extent store layer **350**), the "number of outstanding entries to volume layer" may be incremented indicating the number of log entries (i.e., operations) not yet completed. Notably, the number of outstanding entries to volume layer field **737** records a number of outstanding (i.e., incomplete) I/O operations existing in the log at the time that the entry is created. Recovery to the last host write request may be accomplished by replaying (in temporal order) writes that were pending in the storage I/O stack at the time of the last entry of the log. This may be performed by (i) traversing back from the last (i.e., tail) entry a number of outstanding entries to volume layer **737** recorded in the tail entry, and (ii) playing the traversed entries in order from the oldest entry up to and including the tail entry.

FIG. **7*b*** illustrates replay of the persistence layer log from NVRAM. Once a tail **720*a*** of the log **700** in NVRAM **280** is found as described above, replay of the log may begin from the earliest entry whose data was outstanding (i.e., earliest incomplete I/O) in the storage I/O stack. As described above, the head offset **718** and tail offset **719** are illustratively maintained in memory **220** and not in NVRAM **280**. The outstanding entries to volume layer **737** of the tail **720*a*** indicates a number of log entries to traverse back (i.e., backwards) when replaying the log **700**. Illustratively, two entries **720*b*-*c*** are traversed back corresponding to an outstanding entries to volume layer indication of 2 in the tail entry **720*a***. That is, replay of the log may begin at entry **720*c*** and proceed to entry **720*b*** and finally to entry **720*a*** (i.e., replay of two latest entries not including the tail). Note, the head **720*d*** of the log need not be determined (i.e., found), because replay is performed based on the number of outstanding I/Os in the storage I/O stack from the time of the last (i.e., tail) entry, not from the head **720*d*** of the log.

FIG. **7*c*** illustrates advancement of the persistence layer log in memory. In an embodiment, advancement (i.e., moving the head) of the log **700** occurs in memory when a contiguous sequence of entries **720** at the head completes their respective I/O operations (i.e., writes of data). Illustratively, a head entry **720*e*** followed by a sequence of entries **720*e*-*i*** within the log **700** are stored in memory **220**. Assume entries **720*e,f,h*** have I/O operations outstanding in the storage I/O stack, whereas entries **720*g,i*** have completed I/O (i.e., write data is stored). When the I/O operation completes for entries adjacent to the head entry **720*e***, the log advances from entry **720*e*** to entry **720*f***. Illustratively, when a set of contiguous entries **720*f*-*g*** adjacent to the head entry complete their respective I/O operations, the log may advance for the contiguous set, e.g., from entry **720*f*** to entry **720*h***. It should be noted that the outstanding entries to volume layer **737** previously recorded in tail entry **720*i*** need not be updated as the log advances; rather as the log advances (i.e., the head of the log advances), the entry that becomes the next head entry may be updated. That is, entry **720*f*** may be updated with a number of outstanding entries to volume layer **737** (illustratively 2) when entry **720*f*** becomes the head of the log. Similarly, when entry **720*h*** becomes the head of the log, that entry may be updated with a number of outstanding entries to volume layer, which may need to account for pending I/Os from one or more new entries **720*j*** at the tail of the log. Note updating of the outstanding entries to volume layer **737** occurs for entries in memory **220**; no update is performed for outstanding entries to volume layer **737** for entries **720** in NVRAM **280**.

In one or more embodiments, the volume layer **340** may record write requests (i.e., parameters **432**, such as offset and length, along with extent key **475**) on the dense tree **444**. The recorded metadata may be logged onto the dedicated log **345** of NVLogs **285** and then pushed (written) to SSD as the log **345** fills. Writing of the log entries to SSD **260** may be effected by a change log operation, i.e., copying operation, that records insertions and deletions performed on the in-core dense tree **444**. Accordingly, the entries of the dedicated log **345** may be retired (e.g., deleted, marked reusable, or a marker written to the log expiring previous entries) once the extent store layer **350** returns an extent key **475** indicating storage of the write data.

Accordingly, a metadata path through the storage I/O stack **300** involves storage of metadata in respective entries of the dedicated logs (NVlogs **285**), i.e., entries of dense trees **444** of the volume layer **340**. In addition, a data path through the storage I/O stack **300** involves storage of write data in the persistence write-back cache **380**, where the write data is organized as one or more extents **470** and provided, e.g., via a memory reference such as a pointer or data message, to the extent store layer **350** and to the RAID layer **360**, where each extent **470** is safely stored on SSD **260** using DMA operation **610***b*.

Power Loss Resilient Paths

FIG. **8** illustrates data and metadata paths **800** of the storage I/O stack **300**. In an embodiment, write data **414** of write request **410** is stored in the persistence layer log (and the persistent write-back cache **380** by a persistence layer instance **331**). The write data is then formed into an extent **470** (and a hash value **472**) and passed to the volume layer instance **341** and then on to an extent store layer instance **351***a* for storage on the array **150**. As described previously, the extent store instance processes the hash value **472** to index into a hash table **482** to either determine an existing table entry (e.g., a possible de-duplication opportunity) or a free entry. Illustratively, if no de-duplication opportunity exists (or the hash value indexes to a free entry), the extent **470** (i.e., write data **414**) is passed to a RAID layer instance **361***a*, which returns a location at which to store the data **414**, e.g., via return parameters or callback **860**, to the extent store layer instance **351***a* (i.e., extent store instance). The extent store layer instance may then load the returned location into an entry of the hash table **482** (location **490**) and record the table entry in the dedicated extent log **355**.

Subsequently, the persistent layer instance **331** may wait until an appropriate volume layer instance **341** has inserted (committed) the extent key **475** and write parameters **432** (e.g., offset and length) into the dense tree **444** and recorded that volume metadata in the dedicated volume layer log **345**. Notably, the volume metadata is not written into the volume layer **340** that resolves the extent **470** for holding the write data until the extent is actually at the SSD **260**. That is, the volume layer instance **341** may not store any useful metadata until it is provided the extent key **475** for the extent **470**, and the extent store layer instance **351** does not provide the volume layer instance with the extent key **475** until it has resolved a potential de-duplication opportunity. During this period, the outstanding entries to volume layer **737** in the persistence layer log entry **720** associated with the extent may be incremented. Once the extent key **475** and write parameters **434** are committed into the dense tree **444**, the volume layer instance **341** may issue a callback **822** to the persistence store layer instance **331** informing the persistence layer instance that the write request **410** is "complete." Note, as described above, after completion of sufficient operations to drain the log, the outstanding entries to volume layer **737** in the head entry **720** of the log **700** (i.e., persistent layer log **335**) may be decremented to indicate this condition.

In an embodiment, the dedicated logs **335** and **345** may be stored on a different storage array **150***b* via a different extent storage layer instance **351***b* from that used to store the write data **414** of extent **470**, i.e., storage array **150***a* via extent store instance **351***a*. In other words, the path for (write) data may differ from the path for metadata. Nevertheless, even if appropriate log entries in the dedicated logs **335** and **345** are not immediately stored on the flash components of the SSD **260** (or power is lost) the log entries are preserved in NVRAM **280**, e.g., in NVlogs **285**. Similarly, the write data **414** of the extent **470** is preserved in NVRAM **280**. Thus, the preserved write data and metadata may be replayed to recover failure of either storage array **150***a* or **150***b* (e.g. power loss to the SSD **260**) to enable successful storage of the write data (and/or metadata) to the flash components of their respective SSDs. Correspondingly, there is no particular motive to quickly write the extent **470** (write data **414**) from the persistent write-back cache **380** to SSD, provided there is sufficient storage capacity in the write-back cache **380** to accommodate the write data awaiting storage on SSD. As a result, disjoint operations between instances of layers of the storage I/O stack **300** may be performed in parallel.

The foregoing description has been directed to specific embodiments. It will be apparent, however, that other variations and modifications may be made to the described embodiments, with the attainment of some or all of their advantages. For instance, it is expressly contemplated that the components and/or elements described herein can be implemented as software encoded on a tangible (non-transitory) computer-readable medium (e.g., disks and/or CDs) having program instructions executing on a computer, hardware, firmware, or a combination thereof. Accordingly this description is to be taken only by way of example and not to otherwise limit the scope of the embodiments herein. Therefore, it is the object of the appended claims to cover all such variations and modifications as come within the true spirit and scope of the embodiments herein.

What is claimed is:

1. A system comprising:

a central processing unit (CPU) of a node coupled to a plurality of solid state drives (SSDs);

a memory coupled to the CPU and configured to store a storage input/output (I/O) stack having a plurality of layers including a persistence layer executable by the CPU, a portion of the memory configured as a volatile log to store write data associated with one or more write requests, the persistence layer configured to organize the write data into one or more extents that are copied to the SSDs, the volatile log organized as a data structure having a front-end and a set of records with metadata, the metadata including a head offset referencing an initial record and a tail offset referencing a final record; and

a non-volatile random access memory (NVRAM) coupled to the CPU and including a non-volatile log configured to store the one or more write requests including the write data, the non-volatile log further configured to store the front-end and the set of records when copied from the volatile log, without storing the head offset and the tail offset, to eliminate copying of the head offset and the tail offset to reduce an amount of metadata copied to the NVRAM.

2. The system of claim **1** wherein the persistence layer is further configured to delay copying of the one or more extents to the SSDs depending upon a size of the non-volatile log.

3. The system of claim **1** wherein each record of the set of records includes the write data of a write request.

4. The system of claim **1** wherein the front-end and the set of records are copied from the volatile log by one or more direct memory access (DMA) operations.

5. The system of claim **4** wherein a first DMA operation is used to copy a contiguous record from the memory to the

NVRAM and wherein a second DMA operation is used to copy the write data as the one or more extents to the SSDs.

6. The system of claim **4** further comprising a system interconnect configured to couple the NVRAM to the CPU, wherein the system interconnect has a limited bandwidth.

7. The system of claim **6** wherein eliminating copying of the head offset and the tail offset reduces a number and duration of the DMA operations over the limited bandwidth of the system interconnect.

8. A method comprising:

executing, by a node coupled to a plurality of solid state drives (SSDs), a storage input/output (I/O) stack having a plurality of layers for organizing the SSDs;

storing write data associated with one or more write requests to the SSDs in a volatile log in a memory, the write data organized into one or more extents that are copied to the SSDs, the volatile log having a front-end and a set of records with metadata, the metadata including a head offset referencing an initial record and a tail offset referencing a final record; and

copying a portion of the one or more write requests including the write data to a non-volatile log maintained in a non-volatile random access memory (NVRAM), the copying to copy the front-end and the set of records from the volatile log without copying the head offset and the tail offset, to reduce an amount of metadata copied to the NVRAM.

9. The method of claim **8** further comprising:

delaying copying of the one or more extents to the SSDs depending upon a size of the non-volatile log.

10. The method of claim **8** wherein each record of the set of records includes the write data of a write request.

11. The method of claim **8**, wherein the copying is performed by one or more direct memory access (DMA) operations of the node.

12. The method of claim **11** further comprising:

using a first DMA operation to copy a contiguous record from the memory to the NVRAM; and

using a second DMA operation to copy the write data as the one or more extents to the SSDs.

13. The method of claim **11** wherein a system interconnect having a limited bandwidth is used to access the NVRAM.

14. The method of claim **13** wherein reduction to the amount of metadata copied to the NVRAM reduces a number and duration of the DMA operations over the limited bandwidth of the system interconnect.

15. A non-transitory computer readable medium including program instructions for execution on one or more processors, the program instructions when executed operable to:

implement a storage input/output (I/O) stack having a plurality of layers for organizing a plurality of solid state drives (SSDs);

store write data associated with one or more write requests to the SSDs in a volatile log, the write data organized into one or more extents that are copied to the SSDs, the volatile log having a front-end and a set of records with metadata, the metadata including a head offset referencing an initial record and a tail offset referencing a final record; and

copy a portion of the one or more write requests including the write data to a non-volatile log, the portion to include the front-end and the set of records from the volatile log but without the head offset and the tail offset, to reduce an amount of metadata copied.

16. The non-transitory computer readable medium of claim **15** wherein the program instructions when executed are further operable to:

delay copying of the one or more extents to the SSDs depending upon a size of the non-volatile log.

17. The non-transitory computer readable medium of claim **15** wherein each record of the set of records includes the write data of a write request.

18. The non-transitory computer readable medium of claim **15** wherein one or more direct memory access (DMA) operations are used to copy the portion of the one or more write requests.

19. The non-transitory computer readable medium of claim **18** wherein the program instructions when executed are further operable to:

use a first DMA operation to copy a contiguous record from the memory to the NVRAM; and

use a second DMA operation to copy the write data as the one or more extents to the SSDs.

20. The non-transitory computer readable medium of claim **18** wherein the reduction to the amount of metadata copied provides a reduction to a number and duration of the DMA operations over a system interconnect.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 9,152,330 B2
APPLICATION NO. : 14/151443
DATED : October 6, 2015
INVENTOR(S) : Kayuri H. Patel et al.

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the Specification:

Col. 1, line 61 should read:
per second (IOPS) storage systems where recording each

Signed and Sealed this
Fifth Day of April, 2016

Michelle K. Lee

Michelle K. Lee
Director of the United States Patent and Trademark Office